Characterization of infrared detectors for space applications

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ABSTRACT

Over the past decade, Alcatel Space Industries has become Europe's leader in the field of optical payloads for space applications : earth observation in the infrared spectral range, early warning systems, optical payloads for meteorology and sciences. This position was made possible by Alcatel Space Industries' will to develop the assets required for mastering the key performances of optical payloads, i.e. geometrical, modulation transfer function, radiometric and spectral performances. Infrared detectors have a heavy weigh in the performances of infrared payloads, and this leaded Alcatel Space Industries to perform very accurate characterization of infrared detectors.
This paper looks at those figures of merit of infrared detectors which are of interest to optical payload's performances. These parameters are detector sensitivity and associated dispersions, temporal noise and associated dispersions, contributors to spatial noise (pixel to pixel variation of non linearity, spectral response, 1/f noise, dark level variation versus temperature,..), frequency response, modulation transfer function, geometrical detector performances.
The techniques required for detector characterizations compliant with the required accuracies for each of these parameters are described. Performances of test benches available at Alcatel Space Industries are presented, with associated performances: vacuum chambers and cooling test sets, optical sources for radiometric and MTF measurements, electronics for detector power supply, clock generation, video and image processing.

Keywords : infrared detectors, detector characterization, detector performances

1. INTRODUCTION

Alcatel Space has developped a wide experience in the field of infrared for several type of applications, scientific, meteorology, and military. In each of these applications, the detectors have a very important weigh in the performances of the optical payload, requiring very accurate characterizations of infrared detectors.
A first part of this paper presents the detector figure of merits which are of interest to optical payload's performances, focusing on the radiometric performances for which the detector is the main contributor in most applications.
The test benches used to perform the characterizations and the associated performances are described in a second part of this paper.

2. DETECTOR FIGURES OF MERIT

In any type of application the performances of optical instrument may be resumed by:
- its radiometric and spectral performances,
- its MTF performances,
- its geometrical performances.

These performances impact directly the image quality expected by user, even if each of them have a different weigh with respect to the type of application. It is possible to identify the detector figures of merit which contribute to each of these instrument level performances.

2.1 Geometric parameters

Detector geometric performances are not easely described by generic figures of merit, and depend closely of the application and of the detector type. Single monoelements or several associated monoelements geometry description may be very different from linear or 2D arrays. However, for detectors having a large number of photoelements, several families of geometric parameters may be identified:
- Parameters describing the photoelement: they are related to the detector MTF described hereafter, and give the sensitivity in each spatial direction.

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- Parameters describing the distribution of the photoelements centers. These directly impact the instrument geometric performance. These parameters are defined with respect to the theoretical distribution of the pixel centers, and will have at least maximum and standard deviation in each direction (x and y).
- Parameters describing the flatness of the detector: they have an impact on the instrument MTF.
- Parameters describing the coordinate of "average detector" (1D or 2D) with respect to mechanical origin and axes.

The test sets dedicated to the measurements are not described in this paper, as they are closely dedicated to a specific application.

2.2 MTF parameters

Detector MTF is related to several other figures of merit which which are used to characterize infrared detectors.
In the previous paragraph, we have already identified that the geometrical sensitivity of the photoelements in the x and y direction are closely related to the detector MTF. The shape of this sensitivity curve is directly related to the MTF, the vertical edges being associated with the theoretical MTF for a given pixel size.
Parameters like diaphoty (detection in neighbouring pixels due to photon/optical effects), diaphony (detection in neighbouring pixels due to electron/electrical effects) and crosstalk (summing effects of diaphoty and diaphony) also contribute to MTF performance but do not contribute to a better understanding of detector performances, unless in case of high photon flux for which MTF may be difficult to measure directly.
Diffusion is also a parameter which contributes to detector MTF, and quantifies the signal in the non illuminated zones due to optical reflexions or to electrical diffusion inside the detector.
All of these parameters may be required to be measured depending upon the type of applications. Nethertheless, in applications for which the capacity to discriminate spatial frequencies is of interest, the MTF is the most representative of detector performances, and include all the possible effects.
The accuracy which can be obtained in the measurement of infrared detectors MTF with classical methods are given in the following paragraphs.

2.3 Spectral parameters

Spectral parameters are in most of the applications closely related to the radiometric performances. The most important are:
- Spectral response, which contributes to the instrument selectivity of a specified spectral range.
- Pixel to pixel spectral response dispersion, which contributes to the instrument radiometric performances and has to be taken into account in the instrument calibration philosophy.

The methods used in Alcatel Space to measure these parameters are based on on-the-shelves test sets, and will be described very briefly in this paper.

2.4 Radiometric parameters

Radiometric requirements can be very different from one application to another. However, it is possible to identify the detector parameters which will be of interest for any of these applications, with different weighs for each case.

The detector sensitivity may be expressed in several unities which are all strictly equivalent and which are choosen according to the type of detector and for the performance which is of interest:
- Responsivity in V/W or A/W.
- Quantum efficiency.
- Detector signal ouput (in V, A, e-) for a given optical energy.

For infrared detectors, like several other parameters, the detector sensitivity closely depends upon its temperature. The accuracy obtained in the measurement of the detector sensitivity and its associated temperature are described in the following paragraphs.

Two sources of noises can be identified: the temporal sources and, for detectors having a number of pixels higher than one, spatial sources coming from a non perfect correction of the pixel to pixel sensitivity dispersions.
Temporal sources of noise that must be taken into account in most of the applications may be resumed by:
- photonic shot noise, due to optical signal and stray ligth,
- detector dark current, Johnson and 1/f noises,
- detector readout electronics Johnson, kTC and 1/f noises,
- thermal regulation noise.

The theoretical values for each of these noises depends on the type of detector (thermal, quantum photovoltaïc or photoconductive), on the type of readout electronics (CCDs, CMOS multiplexors, amplifiers adapted to the detector impedance) and of the spectral range (in most of the cases thermal constraints increasing with the spectral range). However, these terms may be used to characterize any detector for space applications, and the theoretical approach must be completed by measurements, with an accuracy which will be described in the following paragraphs.
Spatial sources of noise are related to a non perfect correction of the pixel to pixel dispersions. These type of noises concern applications using detectors with a large number of pixels, long linear arrays or 2D arrays, and they increase with the spectral range. The detector parameters which must be quantified in order to master the contribution of spatial noise in a given application are:
- Dark current variation with tempetature and associated pixel to pixel dispersion.
- Signal variation with temperature and associated pixel to pixel dispersion.
- Non linearity of the signal with respect to the optical flux, and associated pixel to pixel variation.
- Pixel to pixel differential 1/f noise.

The measurement of such parameters are closer from accurate signal levels measurements than from noise measurements. The techniques used to measure these parameters and associated accuracy will be described in the following paragraphs.

The measurements related to other detector parameters which are more specific to one application are not described in the present paper: frequency response, saturation, effect of polarization on the sensitivity. The figures of merit which are a combination of sensitivity and noise , Noise Equivalent Power, Noise Equivalent Irradiance, Specific Detectivity are not discussed in the present paper and not commonly used in detector characterizations in Alcatel Space, as we consider that they are not the best suited figures of merit for a deep understanding of the detector performances.

3. CHARACTERIZATION OF INFRARED DETECTORS

3.1 Detector characterization

For each of the parameters described in the previous paragraph, several types of test sets and test procedures can be identified. The tests sets available in Alcatel Space are described in § 3.2, and the performances achieved in the measurement of the detector parameters are described in § 3.3.

Measurement of the spectral parameters may be performed by a monochromator associated with a blackbody and a reference detector, or by a Fourier transform spectrometer using the interferences from two reflecting surfaces to detect the energy at a given wavelength. Even if comparison have been made between the two methods which shows that the spectrometer allows a better accuracy, the well known and mastered monochromator solution is currently used for our applications.

For measurements of detector MTF, several tests sets are possible: spot scanners, line scanners and knife edges. trade offs have been performed and the knife-edge configuration has been the most currently used due a better accuracy in the detector MTF for a given spatial frequency and the characterization of detector behaviour for a higher number of spatial frequencies.

For measurements of radiometric parameters, the most accurate configuration uses a blackbody whose radiance can be accurately calculated from its temperature, with no focusing optics inserted between the blackbody and the detector under test. In any radiometric test configuration, the blackbody has to operate in vacuum to prevent degradations of radiance due to convexion and atmospheric transmission effects.

In most of the cases, the infrared detector has to be operated at a low temperature and requires to be mounted in a dewar. For radiometric measurements, the blackboby also needs to be cooled and requires a vacuum chamber.
The vacuum chambers available in Alcatel Space allow all possible configurations: detector and blackbodies in the same vacuum chamber operating at two different temperatures, detecteor in its own dewar coupled with optics in a vacuum chamber. In any case, the solution retained for cooling any of the devices is based on the use of liquid Nitrogen and Helium associated to a thermal regulation, and has the advantage compared to active coolers solutions to be more flexible and adapted to any application, well mastered and easy to operate.

3.2 Test sets in Alcatel Space

Figur 3.2.a shows a classical radiometric test configuration. The main subsystems are described hereafter.

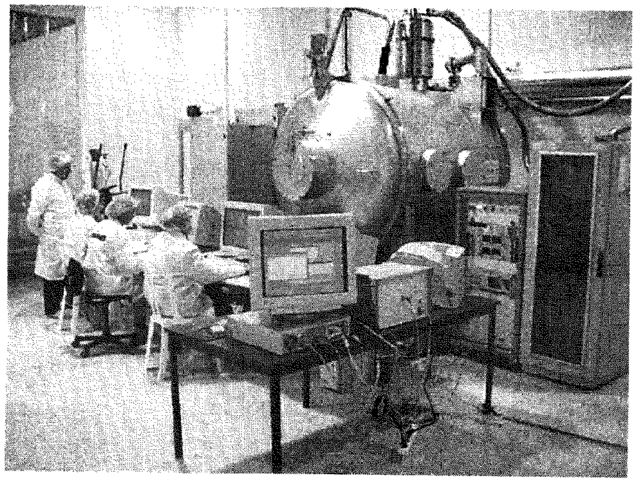

FIGURE 3.2.a: radiometric test configuration

3.2.1 Vacuum chambers

Figure 3.2.a shows one of the several $1m^3$ vacuum chambers available in Alcatel Space for operation of infrared detectors and associated cooled optics. These chambers have useful volumes between ∅ 0,4 m x 0,5 m and ∅ 0,9 m x 0,9 m. Each of them are compatible with temperatures from 4 K to 300 K with liquid Nitrogen or Helium associated with an active thermal regulation, and pressures between 10^{-5} and 10^{-7} Torr are reached by using turbomolecular, diffusion pumps, or cryopumps. Each of these chambers is equipped with connectors with a minimum of 7 x 37 wires. Several optical windows can be adapted according to the requirements of each test.
One of these vacuum chambers is connected to a class 100 clean room for integration of unprotected detectors or of optics requirering this cleanliness.
One additional $1m^3$ vacuum chamber which can reach 80 K is coupled with an optical bench for infrared camera alignment.
Larger vacuum chambers are available at Alcatel Space, ranging from 10 m^3 to 550 m^3, which are used for configurations more complex than single detector testing.

3.2.2 Blackbodies

In most of the configurations, the blackbody is maintained by a tape on the chamber. The best fitted blackbodies in term of emissivity are cavity types with diffuse walls and large area-to-opening ratio. However, this type of device has the drawback of taking a longer time to stabilize to a given temperature, due to the larger mass and volume. A compromise solution has been choosen for nearly every of our test configuration, which is a disk with a roughened surface covered with high emissivity painting. This solution leads to a blackbody whose temperature can be stabilized in tipically half an hour, but with an emissivity reduced tipically to 0,95. In order to limit the risk of possible stray light linked to this emissivity lower than 1, the blackbody is shielded at LN2 or LH2 temperature.

3.2.3 Electronics

Electronics are constituted of several subunits which are flexible and adaptable to various type of detectors operating in a wide frequency range.

The preamplificators are generally specific to the detector and application. The video processing has an accuracy of 16 bits and can operate at a frequency of 1 MHz. For frequencies up to 10 MHz, the accuracy of the video chain is 14 bits. For detector having a CCD multiplexor, a correlated double sampling can be implemented in the video chain.
A subunit is dedicated to the generation of low voltage detector power supplies. Up to 24 power supplies can be generated in the range [0-20 V]. The grounding of the system has been optimized and noise levels of $10nV/\sqrt{Hz}$ are obtained on several MHz.
An other subunit is dedicated to generation of clocks which can be necessary to operate the detector. Up to 32 clocks at frequencies below 50 MHz can be generated. The level shifting of the low and high level of each clocks can be performed up to 20 V. Rise and fall tine can be adjusted with precision of 1 ns for optimization of detector operation.
Digitized datas can be processed with software which allow to extract the figures of merit that have been discussed in the previous paragraphs.
This electronic test set allows to operate most of the possible detectors with a very few hardware and software adaptation.

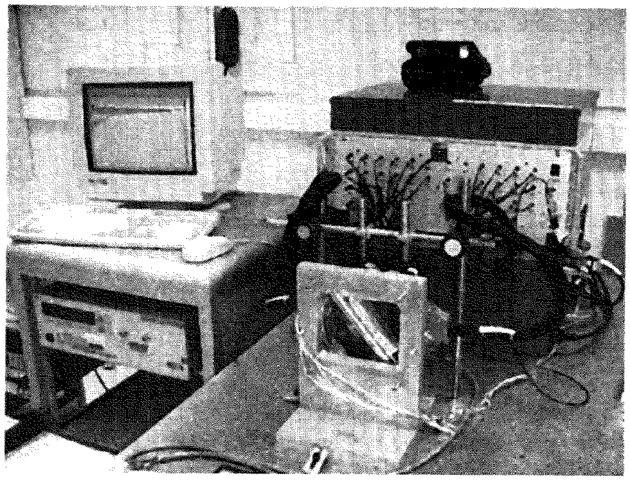

FIGURE 3.2.b: detector test with frame grabber

3.2.4 Temperature measurements

Temperature measurements are made in most of the case using Platinium Resistance Thermometers using the four lead method. The readout is performed by a high performace voltmeter, HP 3458 type.
These temperature measurement are necessary for the detector temperature, in particular to identify with a high accuracy the dispersions linked to detector temperature unstability for spatial noise estimation, and also for monitoring the blackbody temperature, in particular for detector linearity measurements.

3.3 Test sets performances

To the described test sets correspond an accuracy for the detector parameters described in the previous paragraphs: radiometric, spectral and MTF parameters and detector temperature.

3.3.1 Radiometric parameters

The accuracy on the detector sensitivity parameters (responsivity, quantum efficiency, detector signal output) can be degraded by the 5 following factors:

- temporal noise on signal,
- non-linearity of the video processing electronics,
- digital data processing,
- knowledge of the gain of the preamplifier and of the video processing electronics,
- detector thermal stability.

The first factor is made very small by averaging a sufficiently high number of acquisitions. The linearity of the video processing electronics is better than 2 LSB on 16 bits, and does not degrade significantly the signal measurements. Digital data
processing and detector thermal stability are neglectable beside the most significant factor which are the knowledge of first the preamplifier gain an second the video processing chain. Taking into account these factors of degradation, the accuracy is approximately 2 %.

To these electronic factors, it is necessary to add the factors inducing unaccuracies on the knowledge of the photon flux used for sensitivity measurements: the contributors are in this case the errors on:
- blackbody emissivity,
- filters and optical windows transmissions and emissivity,
- wavelength digitization,
- blackbody temperature,
- windows temperature stability,
- diaphragm diameter,
- detector/diaphragm centering,
- detector/diaphragm parallelism.

The error on the blackbody emissivity is the most important, and after comes the error due to the necessity to digitize the wavelength for the signal responsivity calculations, and the errors on optics transmissions. These factors lead to an accuracy of approximately 5 %.

Electronic and optical contibutors being independant, one may consider that the accuracy obtained on the sensitivity of the detectors is approximately 5,5 %.

For the detectors parameters which have to be quantified to master the contribution of spatial noise, ie pixel to pixel dispersions, the accuracy of the measurements is degraded by a combination of temporal noises on the signal and of detector thermal stability. The pixel to pixel variation of optical flux is related to the geometrical field of views and does not have to be considered as an error contributor. In order to reduce the temporal noise, the number of acquisitions is increased, which also increase the time of acquisition, and so the detector stability which can be critical for some detector and cooling system configurations. An optimum has to be found for the number of acquisitions to perform, and an accuracy of 2.10^{-4} is commonly reached for the measurement of such parameters.

Detector linearity measurement can be degraded by the 4 following factors:
- temporal noise on signal,
- non-linearity of the video processing electronics,
- digital data processing,
- detector thermal stability.

Non-linearity of the video processing electronics, more specifically the preamplifier and the clamp when it is required, is the most important contributor and allows an accuracy of 5.10^{-5} which will depend on the level of signal.

To these electronic factors, have to be added the optical factors which contribute to the degradation of the linearity measurement:
- wavelength digitization,
- blackbody temperature,
- window temperature stability.

The highest weigh factor is the mastering of the blackbody temperature in the range required for the lineaity measurements. The accuracy obtained is 2.10^{-4} which will also be the accuracy of the linearity measurements.

Accuracies on the noise measurements are lower than for the signal. It is possible to estimate the accuracy on the noise measurement B by the following expression:

$$\frac{\Delta B}{B} = \frac{\sqrt{B^2 + 4.(\Delta S)^2} - B}{B}$$

The accuracies ΔS on the signal measurements have been defined, and give an accuracy on the noise level which will be better if the signal uses all the dynamics of the acquisition chain. The typical levels obtained are between 5 % for signals which use most of the dynamics, and 50 % for low level signals.

3.3.2 MTF parameters

The most important sources of error applied to the knife-edge method for measurements of the MTF parameters are:
- the spatial sampling when defiling the edge on the detector,
- the focusing optics MTF,
- the microvibrations,
- the focusing unaccuracies due to unparallelism between detector and optics mount.

Optics MTF is often the preponderant factor. Depending on the summation rules, the MTF parameters are measured with an accuracy between 3 and 6 %.

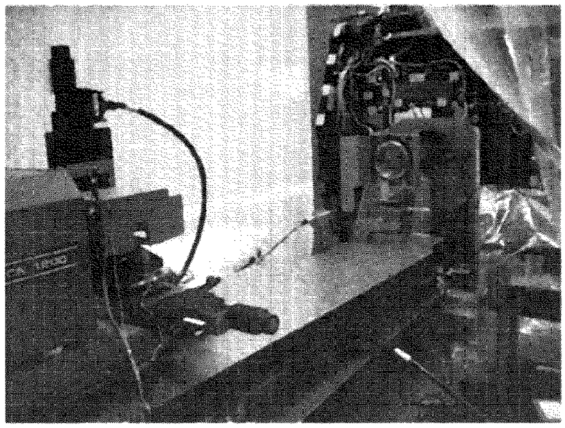

FIGURE 3.3.a: detector MTF test configuration

3.3.3 Spectral parameters

The precision of the monochromator method is mainly due to the accuracy of the reference detector. The contribution of the wavelength resolution may be a significant factor for some applications, like the atmospheric transmission if no precautions are taken on this point. The possible accuracy depends a lot of the wavelength range of interest, the value of 5 % being the typical value for the relative spectral response, and of 0,1 % for the pixel to pixel spectral response dispersion.

3.3.4 Temperature measurements

The accuracy of the temperature measurements are mainly due to the Platinium Resistance Thermometers using the four lead method. The temperature measurement accuracy is 200 mK on a 300 K temperature range, and an accuracy of 10 mK on a 50 K temperature range.

4 CONCLUSIONS

The main infrared detectors figures of merits have been identified in this paper. These parameters are of interest for most of the optical payloads for space applications in Alcatel Space. The assets available in Alcatel Space to characterize infrared detectors have been briefly described, with the accuracies achievable for the most important parameters. These accuracies are resumed on the table 4.a.

Detector figure of merit	Typical accuracy achieved
Responsivity/quantum efficiency	5,5 %
Pixel to pixel response dispersions	0,02 %
Linearity	0,02 %
Temporal noise	5 to 50 %
Detector MTF	3 to 6 %
Relative spectral response	5 %
Pixel to pixel spectral response dispersion	0,1 %

Table 4.a: Performances of the characterization test sets.